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EFFECTS OF FOUR SURFACING METHODS ON SURFACE PROPERTIES AND COATING PERFORMANCE OF RED OAK WOOD

Bruna Ugulino[1], Roger E. Hernández[1]
[1] Université Laval, 2425 rue de la Terrasse, Québec City, CANADA
bruna.oliveira.1@ulaval.ca, roger.hernandez@sbf.ulava.ca

ABSTRACT

The performance of a coating on wood is influenced by many factors, including surface machining before coating. In an attempt to determine a suitable method of surface preparation for red oak wood, the effects of machining processes on surface properties and coating performance were studied. Aside from two traditional surfacing methods preceding coating, sanding and peripheral planing, two alternative methods were evaluated: helical planing and oblique cutting. Surface quality was assessed through roughness, SEM and wettability analyses. Adhesion tests before and after an accelerated aging were carried out to evaluate the performance of a solvent-borne coating. Results indicated that sanding produced surfaces with the lowest roughness values. However, SEM analysis revealed that these surfaces had the highest cell damage, which was assumed to be responsible for increased surface energy and improved coating adhesion after weathering. Oblique cutting and helical planing produced surfaces with similar features. The highest loss in adhesion after weathering was founded on helical and peripheral planed surfaces. Furthermore, oblique cutting samples provided long-term adhesion strength similar to sanding.

Keywords: red oak wood, sanding, peripheral planing, helical planing, oblique cutting.

INTRODUCTION

Several factors affect the coating performance on wood such as surface preparation prior to coating. Red oak, one of the most valuable species in the North America, is largely used for furniture, flooring, interior trim, and veneer. Thus, knowledge of the effect of different surfacing methods on these surfaces in order to improve its preparation and enhance the coating adhesion is of great interest. The most common surfacing method prior to wood coating is sanding. However, this process is one of the most skill-based, time consuming, and expensive operations in wood industry (1). Peripheral planing is a common machining process in woodworking and provides a good surface finish. Helical planing could be used in order to reduce dependence on sanding and improve surface adhesion. Previous study has reported that helical planing provides surfaces with improved wetting properties, good fibrillation, and virtually no cell crushing (2). Oblique cutting produces surfaces virtually free of cell crushing (3).

Wood surface properties affect application and performance of wood coatings (4-5). One important characteristic to assess the quality of machined wood surfaces is the process roughness which can be related with coating performance. However, roughness alone cannot completely describe the machined surfaces. Scanning electron microscope (SEM) micrographs are often used as a qualitative analysis of machined wood surfaces and can corroborate with surface roughness evaluation. Another important analysis that provides valuable information about the coating performance is the wetting behaviour of wood surfaces prior to coating. Wetting of the surface by an adhesive is a necessary prerequisite to bond formation (6). Coating performance can be assessed through adhesion strength and weathering tests. Adhesion strength is measured by several methods such as pull-off method. Accelerated weathering test provides valuable information about durability of wood-coating system in a shorter time than natural weathering. In this context, the purpose of this study was to investigate the effect of four surfacing methods on red oak surfaces regarding surface properties and coating performance.

MATERIALS AND METHODS

Material

One hundred twenty kiln dried boards of red oak (*Quercus rubra* L.) wood were used in the present study. Before planing, boards were stored in a conditioning room at 20°C and 40% relative humidity (RH) until they reached 8% equilibrium moisture content (EMC). Boards were then oriented in the longitudinal direction and machined at 900 mm (L) length, 60 mm (T) width, and 20 mm (R) thickness. Machined boards were divided into four groups, and each of them was submitted to a machining treatment. After treatments, samples for microscopy (10 mm L), roughness (50 mm L), wettability analysis (130 mm L), and coating application (630 mm L) were re-sectioned from each specimen. Samples were then coated and cross-cut in two matched samples. One section of each sample was submitted to an accelerated aging treatment and the other remained untreated before the adhesion test.

Machining treatments

Sanding, oblique cutting, peripheral, and helical planing were used to prepare the red oak surfaces prior to coating. Initially each surfacing treatment at different levels of machining parameters was analyzed separately with the purpose of selecting the best condition of each treatment for varnishing purposes. Costa sander equipped with close-coat paper-backed sanding belts was used to sanding treatment. Boards were submitted to a 100-150-grit sanding program with aluminum oxide sandpaper. Sander feeding was carried out in the fiber direction at 14 m/min feed speed. Oblique cutting was performed with Marunaka Super Meca set up with 15° oblique angle. Feed speed and cutting depth used were 65 m/min and 0.02-mm, respectively. Freshly sharpened high-speed steel knife had 32° knife angle and 58° rake angle. Peripheral planing was performed with a straight-knife cutterhead with 52 mm of cutting radius and was mounted on the horizontal shaft of a Weinig Powermat 1,000 moulder. Knife used for cutting were freshly sharpened with rake, knife and clearance angles of 25, 45 and 20°, respectively. Feed speed used was 6 m/min, which corresponded to wavelength of 1.0 mm. Rotation speed of the cutterhead was 6000 rpm with a cutting depth of 1 mm. Casadei R63 H3 24” surface planer was used to carry out the helical planing treatment at a 1 mm cutting depth. Feed speed was 5.5 m/min, which corresponds to wavelength of 1.0 mm. Rake and helix angles were 30°and 14°, respectively. Before each planing treatment, previous cuts were carried out to level samples.

Microscopic evaluation

Machined surfaces were observed with a field-emission scanning electron microscope (JSM-6360LV, JEOL) operating at an accelerating voltage of 15 kV. Two samples for each surfacing method were selected and small cubes (1 cm^3) were prepared to observe the tangential surfaces. The cubes were attached to aluminium stubs and coated with silver paint. The fibrillation level and the presence of open lumens were the parameters used to assess these surfaces.

Roughness

Surface roughness measurements were made using a Micromeasure confocal microscope. A surface of 12.5 mm (L) x 15 mm (T) was analyzed per sample by Surface Map 2.4.13 software using an acquisition frequency and a scanning rate of 30Hz and 3 mm/s, respectively. Roughness parameters were determined by Mountain Software with a cut off length of 2.5 mm combined with a Robust Gaussian filter (7). Mean surface roughness (S_a) was calculated according to ISO 4287 (8). Core roughness depth (S_k) and reduced valley depth (S_{vk}) were calculated from the Abbot curve according to ISO 13565-2 (9).

Wettability and Surface energy

Wetting analyses of machined surfaces were performed with a goniometer (FTÅ D200) at 20°C. Wetting behaviour was assessed by sessile-drop method within 8 hours following surfacing methods. Distilled water, diiodomethane and formamide were used as test liquids. Sessile droplets (2 µL) of liquids were placed with a microsyringe on the surface on each of the thirty replicate specimens per treatment. Measurements were conducted in the longitudinal direction of the fibers. Right and left angles of the drops on the surface were collected at intervals of 0.1s for a total duration of 120s for distilled water and 30s for formamide and diiodomethane liquids. Average of the contact angles was used for the calculation of surface energy by acid-base approach (10).

Coating procedure

Machined surfaces were coated within the first 6 hours following machining. Samples were kept face against face before coating application in order to minimize the risk of contamination. Three coats of a solvent-borne coating were air sprayed at room temperature according to manufacturer's specifications. Wet average thickness was 200-µm. Surfaces were sanded, lightly with 320 grit abrasive paper between the first and second coats.

Accelerated Aging

Prior to aging, samples ends were sealed with paraffin to prevent moisture exchange during treatment. Samples were then placed in a Cincinnati Sub Zero environmental stimulation chamber (WM-906-MP2H-3-SC/WC) and underwent an aging treatment which consisted of four cycles of 48h at 15% RH and 50°C followed by 48h at 90% RH and 50°C. After aging, specimens were re-conditioned at 20°C and 40% RH.

Adhesion tests

Performance of coating film adhesion from aged and unaged samples was assessed by mechanical pull-off test as described in ASTM D4541 (11). A small dolly (20 mm diameter) was glued with a two-part epoxy adhesive on each specimen and allowed to cure for 48h. A circular groove was then made around the dollies to prevent failure propagations out of the tested area. Finally, the dollies were pulled off from the substrate at constant speed in a universal testing machine. The force attained at rupture was recorded and used to calculate the pull-off strength.

Statistical analyses

Statistical analyses were done on SAS statistical package, version 9.4. Pull-off strength results were analyzed as repeated measures design with the mixed procedure. One-way analyses of variance were performed to assess surface roughness and surface energy data. Means-difference comparison tests were made when a significant effect was found at the 5% probability level.

RESULTS AND DISCUSSION

Surface topography

SEM micrographs showed differences among surfaces produced by the four surfacing methods (Figure 1). Helical and oblique-cut surfaces showed similar features. Both machining process generated surfaces with no visible defects (Figure 1A-B). Lumens and rays were visible with slightly ruptured cell walls. Also, plateau-like areas were more frequent on these surfaces than other two surfacing methods. According to some authors (12-13), these areas are probably formed during the cutting action taking place by peeling entire individual cells in, or close to, the middle lamella. Red oak surfaces prepared by peripheral planing showed a more important level of fibrillation when compared with helical planing and oblique cutting. Partial detachment of microfibrils or fibrils groups from cell walls characterized peripheral-planed surfaces (Figure 1C). Sanded surfaces had the highest level of fibrillation than other machined surfaces. Structure of wood cells on red oak surfaces were severely modified by sanding process. The presence of crushed microfibrils and torn cell walls characterized these surfaces (Figure 1D). Furthermore, abrasive grains created micro-grooves along surfaces which were partially filled with dust and damaged tissues. Fibrillation increases the actual surface available for mechanical adhesion that can improve coating bonding (14-17). However, the penetration of coatings or glues into the wood can be limited by the layer of damaged cells on surfaces (18). This suggests that a combination of open lumens and a certain level of fibrillation are desirable to improve coating spreading and perhaps its performance.

Despite of helical planing and oblique cutting had visually showed smoother surfaces than those from other two treatments (Figure 1); these surfaces presented the highest values of average surface roughness parameter (S_a) as shown in Table 1. Peripheral planing had S_a value statistically equal to those found for the processes cited above. Vessels, rays and fibers lumens were clearly visible on these surfaces which probably increased the surface roughness. Average roughness of sanded surfaces was lower and statistically different than the other three surfacing methods. As previously reported, sanded surfaces are more uniform because of the combination of cellular damage and dust filling the lumens (19). This surfacing method alters the cellular structure in such a way that no anatomical roughness is detectable (16, 20). In fact, S_a is a common roughness indicator that represents an overall measure of the texture comprising the surface. Furthermore, previous studies (21-24) have demonstrated that the characterisation of surface roughness only based on the average roughness parameter is not adequate for the evaluation of machining process on porous wood species (like red oak) because this roughness parameter is sensible to extreme values produced by the presence of vessels.

On the other hand, the lowest values of core roughness depth (S_k), which describes the processing roughness (20-21), were found for machined surfaces with helical planing and oblique cutting (Table 1). This roughness parameter reflects the actual process irregularities by showing low anatomical noise. Surfaces prepared by peripheral planing had intermediate values of S_k. The highest core roughness depth value was provided by sanding. This result can be explained by the irregularities in the surface caused by the abrasive grit particles during sanding process, which drastically change the anatomical structures increasing the roughness due to the process (21). Furthermore, the S_k results were corroborated by SEM micrographs (Figure 1), where the effect of different surfacing methods on red oak surfaces can be visualised through the assessment of cell damages in the tangential surfaces.

Samples prepared by oblique cutting, peripheral planing, and helical planing had statistically similar reduced valley depth (S_{vk}) values (Table 1). In contrast, the S_{vk} parameter was significantly lower for the sanding process. S_{vk} roughness parameter is related to wood anatomy

(22-23). This suggests that the presence of opened lumens on surfaces prepared by the three planing processes contributed to increase the S_{vk} parameter by raising the mean line of the roughness profile (19). Moreover, this result confirms the fact that sanding uniformizes the surface and minimizes the influence of wood anatomy (24).

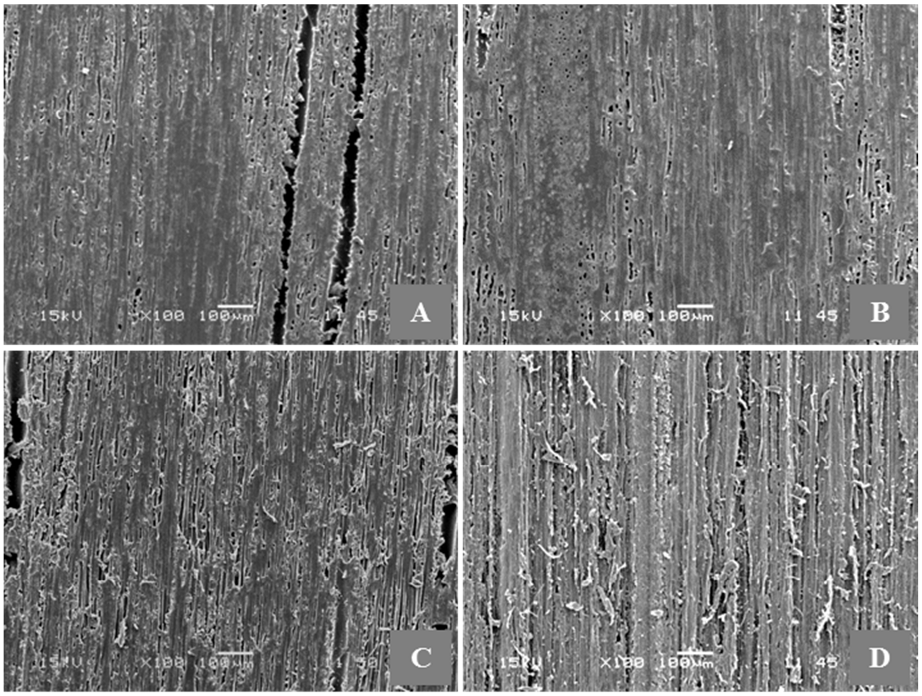

Figure 1: Tangential SEM micrographs of red oak uncoated surfaces produced by helical planing (A), oblique cutting (B), peripheral planing (C), and sanding (D).

Table 1: Surface roughness parameters of red oak wood specimens.

Surfacing method	Roughness parameters (μm)		
	S_a [1]	S_k	S_{vk}
Sanding	8.0^{B2} (1.1)	14.6^{A} (0.4)	38.1^{B} (5.6)
Peripheral planing	15.7^{A} (1.1)	9.8^{B} (0.4)	97.6^{A} (5.6)
Helical planing	16.2^{A} (1.1)	5.1^{C} (0.4)	98.6^{A} (5.6)
Oblique cutting	18.7^{A} (1.1)	5.1^{C} (0.4)	110.9^{A} (5.6)

1 S_a: mean surface roughness; S_k: core roughness depth; S_{vk}: reduced valley depth.
2 Values are means (standard errors of the means) of 30 replicates. Means within followed by the same letter are not significantly different 5% at the probability level.

Wettability

Contact angles as a function of time are presented in Figure 2. Sanding had the fastest wetting, followed by oblique cutting. Peripheral and helical planing showed similar wetting behaviour. The type of process by which wood is machined influences the structure, morphology and chemical composition of its surface, resulting in machined surfaces with different wettability properties. SEM micrographs of red oak samples confirm that sanded surfaces had the most damaged and roughened surfaces than those planed. The high level of fibrillation produced by sanding offered the best condition for water spreading on red oak surfaces. Scratches left by the abrasive grains accelerated the conduction of water by capillary action (24).

Also, the highest total surface energy (γ_s) was observed on sanded surfaces, while planed surfaces showed similar values for γ_s (Table 2). Sanded surfaces had the highest value of disperse component (γ_s^{LW}), followed by peripheral planing, helical planing, and oblique cutting (Table 2). According to Garnier and Glasser (25), γ_s^{LW} component in cellulosic materials depends mostly on the presence and concentration of free hydroxyl groups on the surface. The microfibrils detached from cell walls can increase the amount of the hydroxyl groups available on surfaces. Thus, the higher value of the disperse component on sanded surfaces could be due to the increase of hydroxyl sites exposed at the surface. A more important polar component (γ_s^{AB}) is related to hydrophilic surfaces (26). Surfaces prepared by sanding and oblique cutting presented values significantly higher of this component (γ_s^{AB}), which agrees with the findings of wetting behaviour (Figure 2). Lewis acid parameter (or electron acceptor γ_s^{+}) and Lewis base parameter (or electron donor γ_s^{-}) of surface energy can be used in treating the contribution of acidic and basic characters to the adhesion across an interface (27). γ_s^{-} values were much higher than those of γ_s^{+} for all machining treatments (Table 2). This means that these surfaces are able to participate in polar interactions with acid materials. Sanding and oblique cutting showed similar values of both γ_s^{+} and γ_s^{-} components, which could indicate that these surfaces may exhibit similar performance after coating.

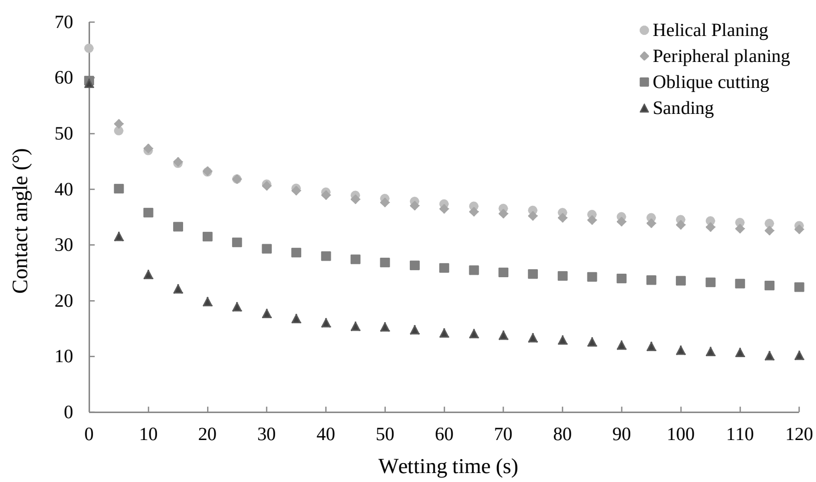

Figure 2: Dynamic contact angle changes of distilled water as a function of time on red oak samples prepared by four different surfacing methods.

Table 2: Mean difference comparisons performed on the data of surface energy components for red oak wood specimens.

Surfacing method	γ_s^{1}	γ_s^{LW}	γ_s^{AB}	γ_s^{+}	γ_s^{-}
Sanding	59.4^{A2} (0.2)	50.3^{A} (0.2)	9.1^{A} (0.3)	1.5^{B} (0.1)	16.1^{A} (1.0)
Peripheral planing	55.3^{B} (0.2)	48.1^{B} (0.2)	7.2^{C} (0.3)	2.5^{A} (0.1)	6.1^{C} (1.0)
Helical planing	54.7^{B} (0.2)	46.2^{C} (0.2)	8.5^{B} (0.3)	2.4^{A} (0.1)	9.0^{B} (1.0)
Oblique cutting	54.8^{B} (0.2)	45.3^{D} (0.2)	9.6^{A} (0.3)	1.6^{B} (0.1)	17.8^{A} (1.0)

1 $\gamma_{s:}$ total surface energy; γ_s^{LW}: disperse component; γ_s^{AB}: polar component; γ_s^{+}: electron acceptor component; γ_s^{-}: electron donor component.
2 Values are means (standard errors of the means) of 30 replicates. Means within followed by the same letter are not significantly different at the 5% probability level.

Adhesion performance

The ANOVA showed that pull-off strength was significantly affected by the interaction between surfacing method (S) and aging (A) (Table 3). The effect of the surfacing method on pull-off strength was statistically significant. However, the effect of aging on pull-off strength was statistically more pronounced (Table 3). Results of adhesion and aging tests for four surfacing methods are summarized in Table 4. Before aging, pull-off strength was statistically similar for sanding, peripheral and helical planing. The lowest pull-off adhesion measured was found on specimens planed with oblique cutting (Table 4). After aging, sanded specimens showed the highest pull-off adhesion, while planed surfaces had similar pull-off adhesion. Adhesion results agreed with findings on previous studies (28-31) which reported that fibrillation can improve the adhesion of coatings by increasing the area available for mechanical anchoring. However, the fibrillation could reduce the coating adhesion, if damaged cells are not firmly attached to the surface (31).

Loss of coating-substrate adhesion was statistically similar to specimens machined by peripheral and helical planing. Regardless the lower value of pull-off strength before aging, samples planed with oblique cutting presented loss in adhesion similar to sanding (Table 4). As mentioned before, the certain level of fibrillation presented is perhaps what has ensured a better adhesion of the coating to sanded surfaces after the accelerated aging test. The area between substrate and coating increases as surface roughness increases which could explain the better adhesion of rougher surfaces. The presence of plateau-like areas on planed surfaces with oblique cutting may have been responsible for the low value of pull-off strength before aging. However, the availability of opened lumens and rays could have increased the adhesive penetration and decreased the impact of the weathering treatment in these surfaces.

Table 3: F values for pull-off strength analysis obtained from ANOVA for red oak surfaces prepared by four different machining processes.

Source of variation	Pull-off strength
Surfacing method (S)	5.7*
Aging (A)	502.1*
S x A	11.3*

*Statistically significant at the 5 % probability level.

Table 4: Pull-off strength before and after an accelerated aging treatment of an interior coating applied on red oak wood samples.

Surfacing method	Before aging (MPa)	After aging (MPa)	Loss in adhesion (%)
Sanding	6.4^{A1} (0.3)	4.5^{A} (0.1)	29^{B} (2.4)
Peripheral planing	6.7^{A} (0.3)	3.8^{B} (0.1)	42^{A} (2.4)
Helical planing	6.9^{A} (0.3)	3.7^{B} (0.1)	40^{A} (2.4)
Oblique cutting	5.4^{B} (0.3)	3.9^{B} (0.1)	26^{B} (2.4)

1 Values are means (standard errors of the means) of 30 replicates. Means within followed by the same letter are not significantly different at the 5% probability level.

CONCLUSIONS

Helical planing and oblique cutting produced surfaces with no visible defects. Peripheral planing created slight fibrillation, while sanding produced the most cell damage on red oak surfaces. Peripheral and helical planing suffered a significant loss in adhesion after the accelerated aging. Sanded surfaces showed good wettability, high process roughness and adhesion after aging compared to other treatments. The high level of fibrillation promoted long-term adhesion strength on these surfaces. Oblique cutting caused intermediate wettability, lower process roughness and similar loss in adhesion strength to sanding, showing potential for long-term utilization and could be used as an alternative to sanding on red oak surfaces. Further research to optimize the level of fibrillation to ensure better adhesion before aging is necessary.

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